

# Bent Superconducting Solenoids With Superimposed Dipole Fields\*

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## ABSTRACT

Superconducting solenoid magnets with a superimposed dipole field have been proposed for the cooling channel for a future high luminosity muon collider. The magnets are typically bent into a 180° arc with a centerline radius of about 0.5 m and an aperture of 0.3 - 0.4 m. They are characterized by having an on-axis solenoidal field of about 4 tesla with a 1-tesla superimposed dipole field. A cost-effective design is proposed, in which the dipole field is generated by tilting the winding planes of the solenoid coil. The magnetic and mechanical design of such magnets and the proposed manufacturing method are presented.

## 1. INTRODUCTION

The configuration shown in Figure 1.1 has been proposed for the cooling channel for a high brightness Muon Collider [1]. Such magnets can be used for dispersion generation in large emittance beams in particle accelerators. Charged particles traversing a bent solenoid (half of a toroidal magnet) of sufficient field strength are forced into a helical path, i.e. “trapped”. The trapped particles follow paths that progress along the axis of the solenoid; however, due to the magnetic gradient that is present in the toroidal field they tend to drift away from the axis. A dipole field superimposed on the toroidal field in the solenoid compensates for the drift at a given particle energy [2], and particles with different energies are dispersed.

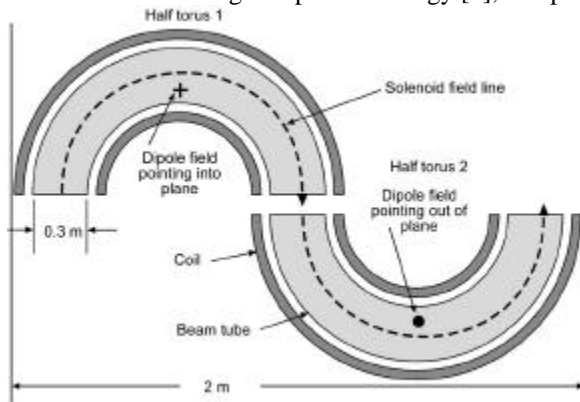


Figure 1.1 Typical arrangement of bent solenoids

One method for obtaining the superimposed dipole field is to tilt the winding planes of the solenoidal turns of the coil. For the 4 T solenoid, a superimposed dipole field of 1 tesla is produced with the winding plane tilted by 25°. Figure 1.2 shows a straight solenoid with tilted winding planes; however, the same principle can be applied to the bent solenoid.

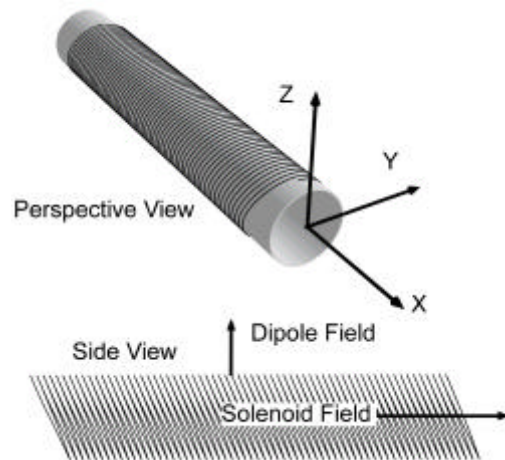


Figure 1.2

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## 2. MAGNET DESIGN FEATURES

### 2.1 General Features

The main components of this magnet assembly are shown in Figure 2.1. A design for a relatively low cost cold mass assembly is obtained by using commercially available stainless steel tube fittings for the inner and outer helium containment shells. The cold mass is designed for an internal operating pressure of 20 atmospheres to allow the use of supercritical helium as the coolant. The necessary rigid structural support of the coil is provided by packs of low carbon steel laminations between the coil and the outer helium containment shell. The outer shell thus serves as the principal coil support member as has been done in both the SSC and RHIC magnets.

The inner and outer helium containment shells are connected at the magnet ends with end plates, one of which contains a bellows to allow for differential contraction between the coil and the outer shell in case there is a thermal gradient during cool down.

The coil design is well adapted to the direct wire computer-controlled coil winding process used by AML. This procedure provides accurate and well-constrained conductor placement by employing a multi-axis coil winder, which automatically lays the conductor in pre-machined grooves in the coil support base. The coil design is discussed in Section 2.3 and the winding machine operation is discussed in Section 5.1.

Some basic parameters for the bent solenoid are listed in Table 2.1

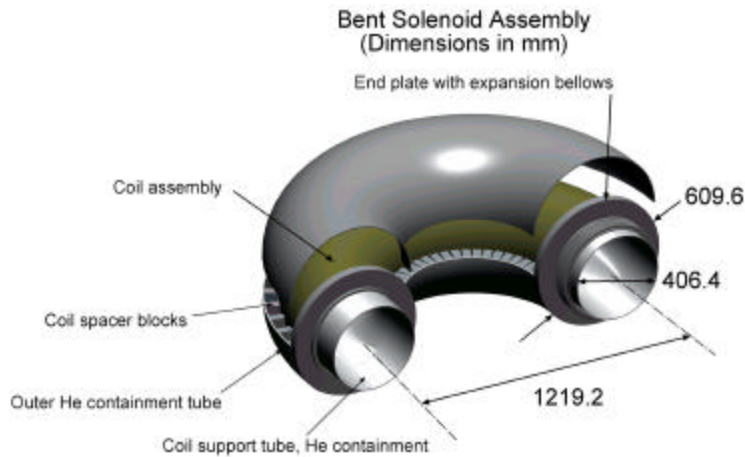


Figure 2.1 Components of the 180° bent solenoid.

Table 2.1 Basic Parameters

Bend radius of coil center line	609.6 mm
Total bending angle	180°
Magnetic length along axis	1915 mm
Coil aperture	416.4 mm
Solenoid field along axis	4 T
Dipole field on axis	1 T
Stored energy	~1.5 MJ

### 2.2 Conductor

A Kapton-wrapped 37-strand flexible round NbTi mini-cable that was developed in a joint effort between AML and Lawrence Berkeley National Laboratory for applications in fusion magnets is well suited for use in this magnet. It has several advantages over the flat “Rutherford-type” cable for this case:

- The round cable can be easily bent in any direction. The Rutherford-type cable requires special cable orientations to accommodate bends, as in the constant-perimeter design for coil ends of accelerator dipoles and quadrupoles.
- A round cable does not show any degradation in critical current due to the cabling process. For a Rutherford-type cable, a degradation of 5-10% is found.
- The multi-strand conductor is flexible enough to be used in a completely automated winding process, which reduces the manufacturing cost of the coils.

The cable properties are listed in Table 2.2 and its cross section is shown in Figure 2.2.

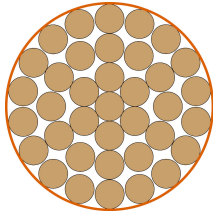


Figure 2.2  
37-strand round mini-cable

Table 2.2 Cable Parameters

Number of Strands (NbTi)	37
Strand Diameter	0.32 mm
Cable Diameter	2.25 mm
Cu/SC ratio	2.26/1
Nominal Strand Jc @ 4.23 K, 6 tesla	2,500 A/mm <sup>2</sup>
Filament diameter	9.8μm
Insulation	Kapton wrap

### 2.3 Coil Configuration

The following guidelines were used for designing the coil with the selected conductor.

- The operating margin is to be about 25%. This is based on a peak field of 6 T on the conductor and a maximum conductor temperature of 4.4 K. (A bent solenoid of the given parameters produces a field of 3 T at the outer radius, 4 T on the axis, and 6 T on the inner radius.)
- Since the stored energy in this magnet is about 1.5 MJ, the inductance should be low enough that the time constant for the magnet energy discharge is long enough for conventional quench protection methods to be effective. This implies that the current should be high but consistent with the stability requirement below.
- A guideline that has been used for superconducting accelerator magnets is to keep the current density in the copper in the range of 700- 900 A/mm<sup>2</sup> in a quench in order to ensure that there is sufficient stability in the conductor to resist spurious and/or training quenches. On this basis, we have selected an operating current of 1550 A which would produce a current density of ~750 A/mm<sup>2</sup> in the copper for the selected conductor. The coil thus requires 8 layers of conductor to produce the 4 T nominal solenoidal field.

A detailed magnetic analysis for a 180° bent solenoid was made with the AML proprietary computer program CoilCAD<sup>TM</sup>. (The results are summarized in Section 3.) However, we can easily determine the magnetizing force necessary to produce a nominal field of 4 T along the axis of a complete 360° toroidal magnet from the relation

$$B_{\phi} = \frac{\mu_0 NI}{2\pi R} = 4.0 \text{ T}$$

where the magnetizing force in amperes/meter is  $NI/2\pi R$  with R as the major radius of the toroid. If the axial field is set to 4 T, the required  $NI = 3.19 \times 10^6$  A/m for  $R = 0.609$  m.

The AML automated coil winding procedure produces a conductor spacing of 2.45 mm (the insulated cable diameter) at the inner radius of the toroid, where  $R = \sim 0.377$  m (allowing 24 mm for the coil thickness). Thus the conductor spacing will be 3.9 mm at the mid-radius,  $R = 0.609$  m. Figure 2.3 is a cross section of a portion of the coil winding at the mid radius.

This conductor spacing produces a magnetizing force of  $257 \text{ turns/m} \times 1550 \text{ A} = 3.98 \times 10^5$  A/m in each layer. From the above equation,  $3.19 \times 10^6$  A/m is required to achieve a 4-tesla toroidal field on the axis; therefore, 8 layers are required for the coil.

The operating margin and other parameters for the magnet are listed in Table 2.3. The critical surface was calculated using Morgan's parameterization [3], which is based on a measured critical current density of 2500 A/mm<sup>2</sup> at 4.2 K and 6 tesla for RHIC NbTi cable. In this proposed coil, the critical current in the cable at 4.4 K and 6 tesla is 2120 A, which gives an operating margin of 27 % at 1550 A. Also, the current density in the copper is 751 A/mm<sup>2</sup>, which is within stability guidelines.

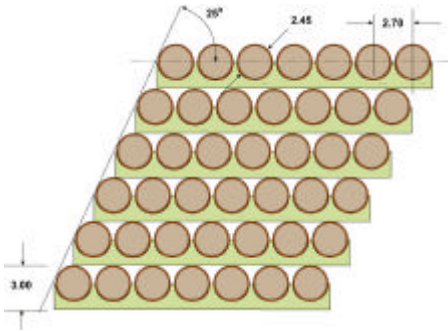


Figure 2.3. Portion of coil winding at mid-radius showing 25° winding plane tilt.

Table 2.3 Operating Parameters

Magnetic length along axis	1915 mm
Coil aperture	416.4 mm
Solenoid field along axis	4 T
Dipole field on axis	1 T
Quench field along axis	5 T
Operating current	1550 A
Operating temperature	< 4.4 K
Inductance	1.22 H
Stored energy	1.47 MJ
Max field on conductor	6 T
Operating margin at 4.4 K	27%
Current density in copper	751 A/mm <sup>2</sup>

### 3. MAGNETIC ANALYSIS SUMMARY

The end effects, the effect of the tilted coils to produce the superimposed dipole field, and the distribution of field across the equatorial plane for a bent solenoid of 180° were computed with the special magnet design software, CoilCAD™. This program was developed by AML to calculate the fields in special shaped magnets. Coil forms are selected from predefined classes, such as dipole, flat pancake, solenoid, toroid, etc. A few parameters fully define the coil form of each class. After a coil has been generated, it can be transformed in many ways (twisted, bent, stretched, etc.) to generate even the most complex coil forms. Coils generated in that way can be combined to larger objects. CoilCAD™ generates the complete 3-D space curve of the conductor and from this space curve calculates the 3-D field at any point.

The geometry used for the field calculation is shown in Figure 3.1. A straight solenoid original pattern was selected and then bent into the prescribed radius. To simplify the creation of the model, a single layer coil was used for the magnetic field calculation with CoilCAD. The results would be the same as for a multiple layer coil since the number of ampere-turns per meter is the determining parameter.

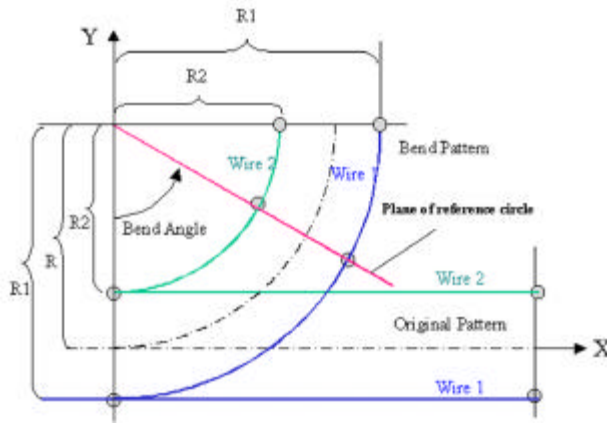


Figure 3.1. CoilCAD Geometry

Figure 3.2 shows the variation of the total field parallel to the axis and across the equatorial plane. Each curve shows the field values along the length of the solenoid for a different equatorial plane radial

distance, ranging from a point near the outer radius ( $r=-195$ ) to one near the inner radius ( $r=+195$ ). These curves show the attenuation of the field near the end of the coil.

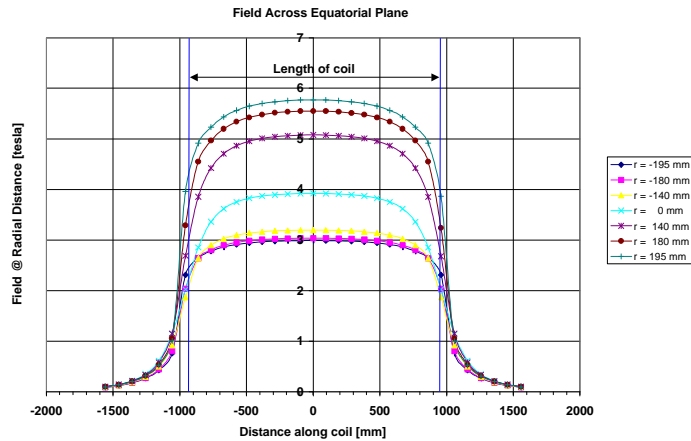


Figure 3.2. Total field in bent solenoid with tilted winding plane. Curves are shown for points across the equatorial plane ( $r=+195$  is innermost).

The dipole field produced by the  $25^\circ$  tilt of the coil winding planes as computed by CoilCAD is shown in Figure 3.3. The end effects are visible as well as the skew dipole component. Thus, the desired 1-tesla superimposed dipole field is produced along with the 4-tesla on-axis solenoidal field for the  $25^\circ$  tilt angle.

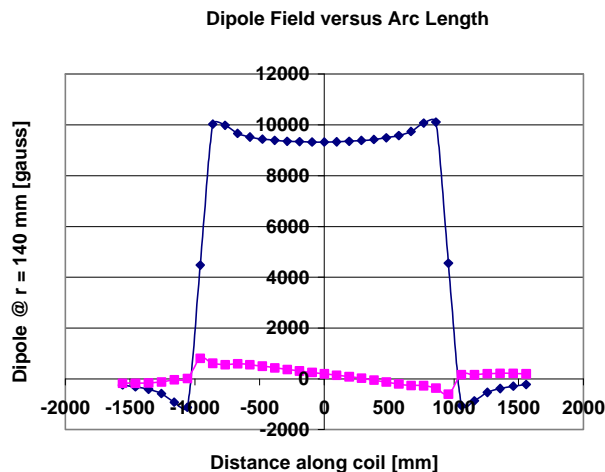


Figure 3.3 Normal and Skew Components of Dipole Field Along Arc Length

## 4. MECHANICAL DESIGN SUMMARY

### 4.1 Design Features

The magnet assembly consists of the coil assembly, its support structure, and the helium containment vessel necessary to maintain the cryogenic environment for the superconductor. The proposed configuration is shown in Figures 4.1 and 4.2.

Superconducting accelerator magnets, such as for RHIC and the once proposed SSC, rely on the use of supercritical helium for cooling the magnet. Until more specific requirements have been set, we have assumed that this technology is used for this application and have used 20 atmospheres pressure as the design requirement for the helium containment. Thus, this design is adaptable to both the supercritical and the low-pressure helium bath cooling.

The helium containment for the bent solenoid requires rather large (i.e. up to 610 mm diameter) pre-formed shells bent to a small radius. Commercially available tube fitting sizes that are consistent with the design requirements can reduce the cost of the assembly. Thus, we have selected standard size tube fitting dimensions for the inner and outer tubes of the vessel. These are available in inch dimensions that closely match metric dimensioning requirements. The inner helium containment tube may be obtainable as a seamless tube fitting in a 300 series stainless steel.

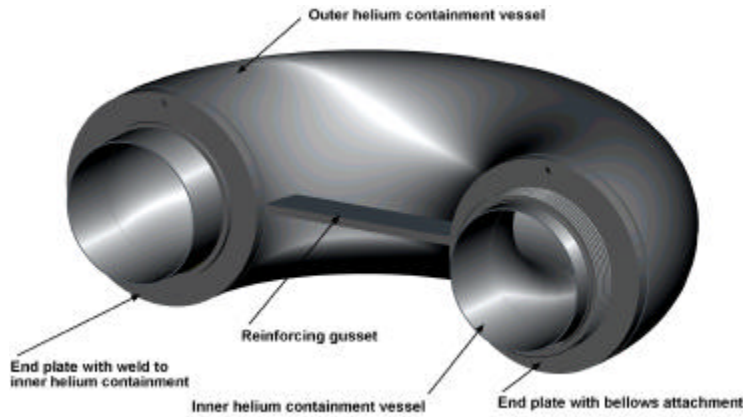


Figure 4.1 Helium containment configuration with support gusset and bellows.

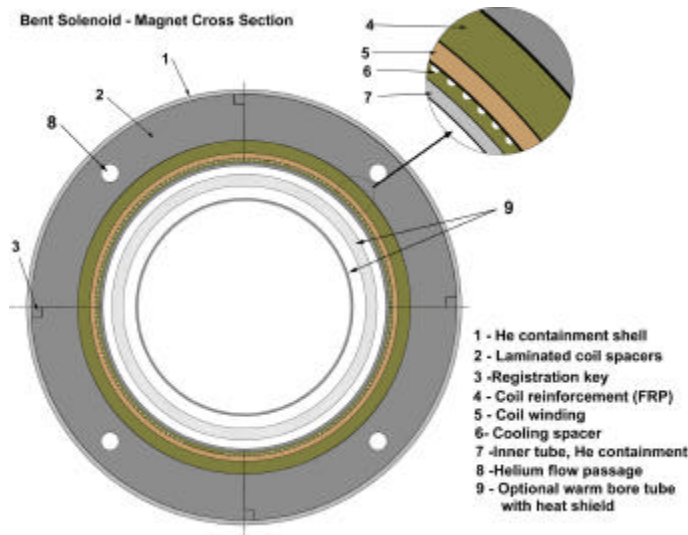


Figure 4.2 Magnet Cross Section

Spacer blocks made of low carbon steel laminations are used to provide precise support of the coil relative to the outer shell. One end of the magnet is fitted with an end plate containing a bellows to allow for differential expansion of the components when cooled to operating temperature. A cross section of this configuration is shown in Figure 4.2.

The magnet may operate in an environment in which there is heat input to the coils from the beam tube; this could be possible by radiation-induced heat or a warm beam tube environment. Thus, a composite tube with cooling channels ("cooling tube") is to be used between the inner helium containment tube and the coil. This will serve to intercept heat coming in from the beam tube to the magnet and will also serve as the support tube on which the coil is wound.

## 4.2 Structural Analysis

A finite element structural analysis was performed on the cold mass using the commercially available code ALGOR [4] with the following models:

- The coil assembly and its support structure under the action of the Lorentz forces
- The helium containment vessel with a load of 20 atm internal pressure
- The helium containment assembly with a thermal load caused by the inner helium containment shell cooling down before the rest of the assembly.

### Coil analysis summary:

At a nominal field of 4 tesla, the Lorentz forces acting on the bent solenoid produce a pressure distribution that varies with the angle from the horizontal plane (from the outer major radius to the inner major radius) as shown in Figure 4.3. This occurs simultaneously with compressive end force of ~136,000 lbs. This load was applied to the finite element model shown in Figure 4.4.



The analysis showed that in a coil assembly of this design, the relatively large Lorentz loading produced by a nominal field of 4 tesla in the magnet will produce relatively low deflections and stresses in the coil. This was demonstrated with a composite coil of 1-inch thickness, supported with spacer laminations and the external helium containment shell. Deflections and stresses for this case are shown in Figure 4.5.

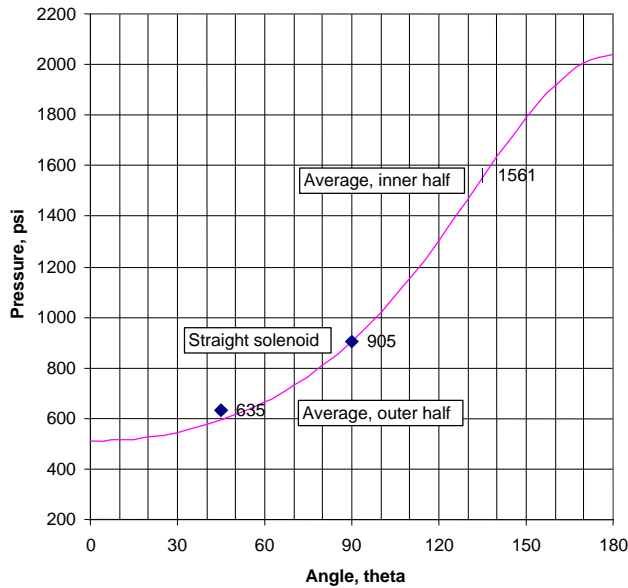


Figure. 4.3 Variation of magnetic pressure within a toroidal magnet with a 4 tesla nominal field

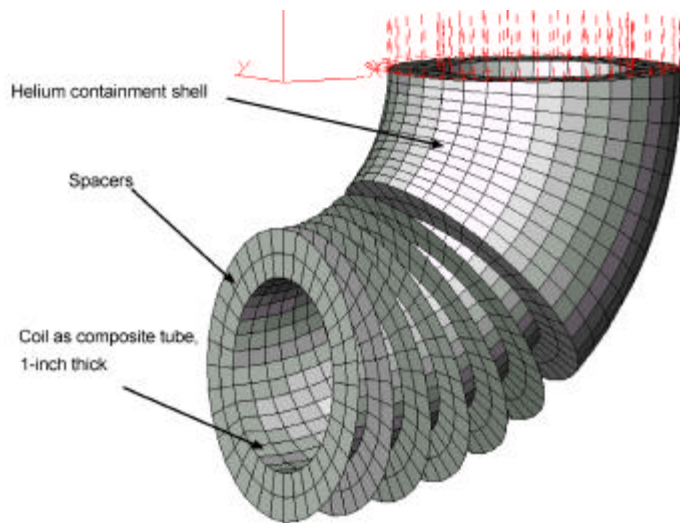


Figure 4.4 Finite element model for coil structural analysis.

#### Helium Containment Structural Analysis Summary:

As indicated above, two separate analyses were performed on the helium containment assembly, one for pressure load and the other for thermal load. This resulted in a configuration that required a reinforcing gusset and a bellows mounted in one of the end plates, as shown in Figure 4.1.

The bellows is required in order to handle a transient thermal load that could occur if the temperature of the inner tube decreases much more rapidly than the rest of the assembly during cool down. A highly magnified plot of the deflected shape of the finite element model of the structure is shown in Figure 4.6.

A stainless steel gusset, typically 25 mm thick and 200 mm wide, would provide enough stiffness to limit the deflections due to the pressure load.

Deflections (inch) and stress (psi) in coil loaded with Lorentz force.  
(Deflections shown at 50x scale.)

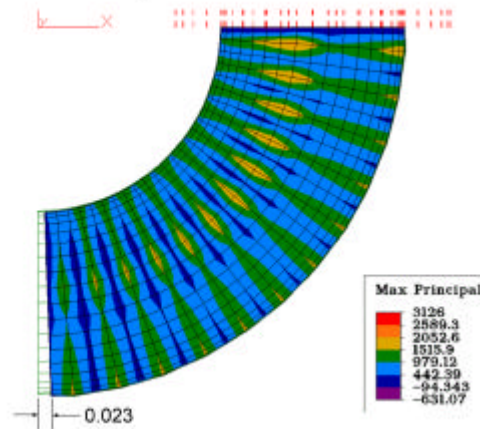


Figure 4.5 Deflections and maximum principal stress.

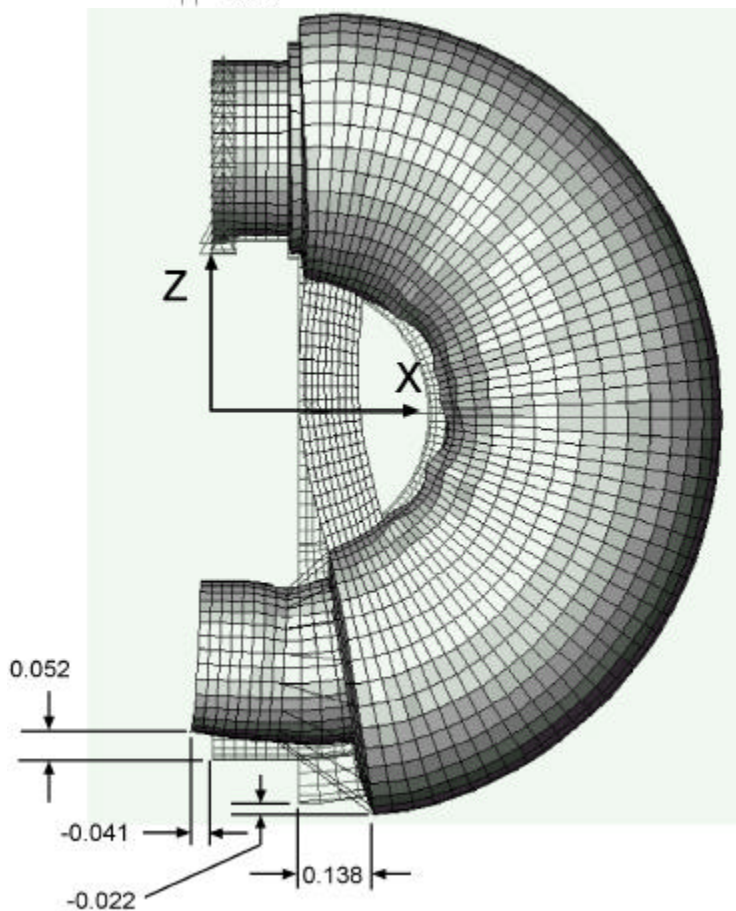


Figure 4.6 Deflected shape of helium containment vessel with 20 atm internal pressure. Deflections are magnified by a factor of 50.

## 5. FABRICATION AND ASSEMBLY PROCEDURES

### 5.1 Coil Winding

A one-third size partial coil was wound on a scaled-down prototype winding machine (shown in Figure 5.1 with its control system). The coil support tube passes through a stationary circular support structure and is mounted at its two ends on the winding fixture. The mounted tube can rotate around the solenoid vertical axis. A winding end effector, which orbits along the path defined by the circular support structure, positions and tensions the conductor.



The layers of the solenoid are separated by thin fiber-reinforced over-wraps that can be machined with the groove pattern for the next layer. This improves the conductor placement accuracy for tilted planes during the winding process and gives additional stability to the coil. After the winding of the coil is finished, it is over-wrapped with epoxy-impregnated fiber-reinforced material. This coil package is precisely machined to fit the laminated steel spacer blocks that surround the coil assembly and provide rigid structural support of the coil from the helium containment shell.

Figure 5.2 shows a sample tilted plane winding made with the 1/3 scale machine.



Figure 5.1. One-third scale coil winder with control system



Figure 5.2. One-third scale bent solenoid sample coil winding.

## 5.2 Magnet Final Assembly

The magnet has been designed in such a way to facilitate final assembly operations without expensive special tooling. Figure 5.3 illustrates the assembly and welding sequence for the bent solenoid. Subsequently the external electrical assembly of the power and instrumentation leads is completed. The magnet will then be put through a series of tests and measurements to obtain electrical and mechanical data such as:

- Hipot verification of insulation integrity
- Resistance measurement of coil
- Dimensional mechanical measurements
- Verification of helium containment integrity with a mass spectrometer leak detector

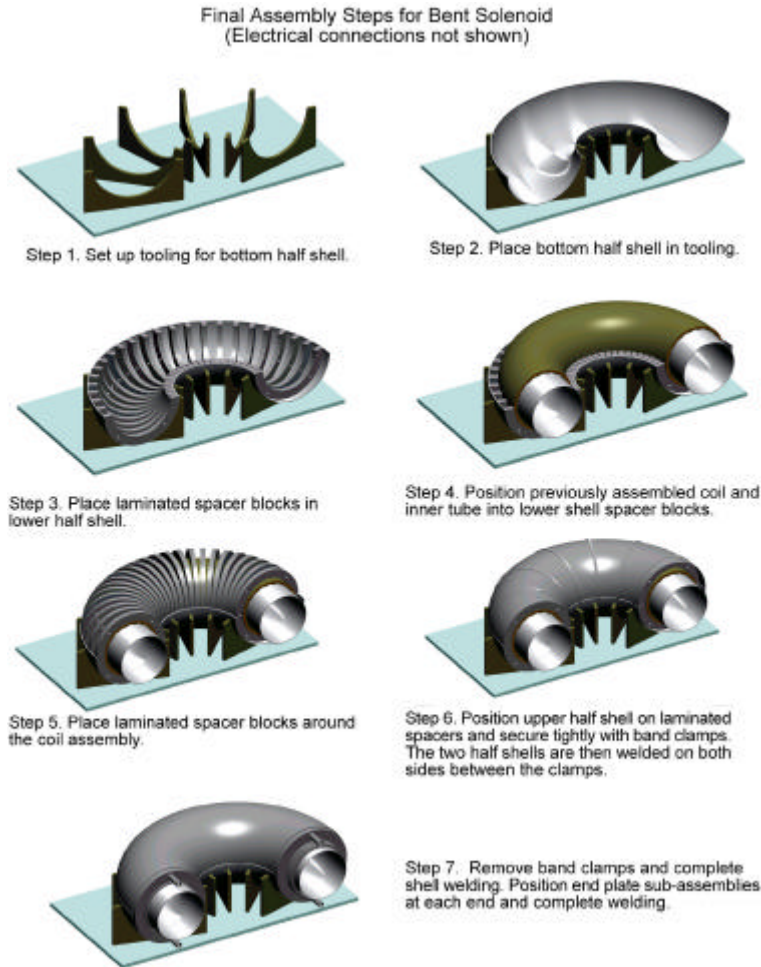


Figure 5.3  
Assembly  
steps

## 6. SUMMARY AND CONCLUSIONS

We have presented a summary of a conceptual design for a 180° bent solenoid with a 4-tesla nominal solenoid field and a superimposed 1-tesla dipole field. The dipole field component has been obtained by tilting the winding planes of the coil by 25° relative to the axis of the solenoid. A detailed magnetic analysis verified the field in the magnet interior and near the ends.

The tilted-plane bent solenoid coil can be wound efficiently and relatively inexpensively using automated coil winding procedures that have been developed by AML. A 37-strand round NbTi mini-cable conductor that is suitable for use in the automated winding machine has been selected. The coil parameters have been chosen to provide an operating margin of about 25% at a temperature of 4.4 K and at a peak conductor field of 6 tesla.

The helium containment vessel has been designed to take advantage of the cost savings that can be obtained by using commercially available sizes of stainless steel fittings. The vessel can be operated at an internal pressure up to 20 atm and the stresses will be within the allowable range of the ASME code.

Some of the remaining issues to be decided prior to completion of the detailed design for a prototype magnet include the following:

- Quench protection considerations based on the large amount of stored energy in the magnet and the relatively large inductance.
- Integration of provisions for a support system for mounting in a cryostat.
- Optimization of the magnetic design based on field quality requirements.
- Any changes to the mechanical design to account for structural optimization based on operating conditions.

## *7. REFERENCES*

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- [3] A New Critical Surface for RHIC NbTi, G. H. Morgan, Brookhaven National Laboratory Memo 560-1 (RHIC-MD-2611), Jan. 6, 1997
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